LIGHTNING PROTECTION OF EXTRA HIGH VOLTAGE TRANSMISSION LINES*

BY

N. RAMA RAO[1]

SYNOPSIS

The protection of extra high voltage transmission lines from lightning is of considerable importance as a result of the excessive flashover rate of such lines in the United States. The problem is quite complex, because the factors involved are many and relatively few accurate data are available. Interest in the subject is evidenced by the large number of publications appearing in recent years. It is the aim of this paper to evaluate critically the various component factors involved in the light of the recent excessive flashover rate of extra high voltage transmission lines.

INTRODUCTION

Basic Philosophy of Protection of Lines Against Lightning Strokes

The present concepts of line protection are based upon direct stroke theory which attributes severe lightning disturbances on any transmission line to direct contact with the line. Prior to acceptance of this theory, lines were designed on the basis of induced strokes. However, tests and experience have proved that such voltages are too low to account for the lightning damage.

Direct stroke theory is now accepted for high voltage lines. Protection against direct strokes is based upon shielding the conductor from lightning and providing adequate drainage facilities and insulation. In the shielding method, there is no possibility of arc formation from line to ground, thereby giving inherent protection. The nonshielding method allows the formation of an arc between the ground structure and conductors and provides means to quench the arc without line interruptions. In the shielding method, the use of a ground wire above the conductor intercepts the stroke, provides a fairly good conducting path to ground, and distributes the current into more paths, thereby reducing the voltage drop. The electric and magnetic components of the voltage induced on the conductor are also reduced.

Survey of Methods

Until 1929, existing methods of calculating lightning performance of transmission lines were based upon the induced stroke concept. In

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[1] Department of Electrical Engineering, Regional Engineering College, Warangal, India.

1931, Fortescue and Conwell (**1**)[2] outlined a method of calculation which assumed that the stroke was essentially a vertical conductor down which a voltage wave travelled. The surge impedance of the stroke was given a fixed value of 200 ohms. The stroke, after contacting the tower, divided into two parts—one part to the tower and the other to the ground wire. The tower was regarded as a vertical section of transmission line having a constant surge impedance of about 100 ohms. The tower-footing resistance was included in the method, and a quantity called the lightning-stroke voltage (the crest value of the wave travelling down the stroke channel) was used. Fortescue (**1**) estimated the effect of corona on coupling factors and the self- and mutual surge impedances of ground wires; he then worked out equations for tower reflections. However, he did not present any wave shapes or numerical calculation. Jordan (**3**) approached the problem with assumptions identical to those of Fortescue, but he worked out the numerical calculations and plotted the resulting wave shapes for a number of cases. In 1934, Monteith (**5**) evolved a simple and practical method for predetermining line performance, based upon assumptions similar to those above. He prepared a number of graphs, plotted in terms of span length, tower-footing resistance, number of insulators, and the minimum midspan clearance.

Bewley (**6**) applied the theories of travelling waves to the lightning problem in considerable detail and with mathematical rigor. He proposed theories for ground wire and counterpoise, and considered successive reflections in a tower. In his calculations, the concept of surge impedance of stroke channel was retained; however, a current (instead of a voltage) wave travelled down the stroke channel. It was, however, realized that the method of representing the stroke channel by a surge impedance is not very sound. To obviate the use of this unknown surge impedance, Hagenguth (**21**) injected a current of desired wave shape into the circuit to represent the stroke current. Harder and Clayton (**31**) made use of this concept and calculated the outage probability curves by means of an analog computer. The basic assumption involved in the use of stroke-probability curves is that lightning is a constant current source, whereas earlier it had been regarded as a voltage source. Bewley in his approach (**6**) retained the concept of surge impedance for stroke channel and utilized the stroke-current probability curves.

Although a considerable amount of travelling wave theory was used in the earlier methods, the tower was represented by the footing resistance because it was felt that the time involved in wiping out the surge impedance of the tower is small compared to the time-to-crest of the lightning voltage wave or of the current wave. The Harder and Clayton (**31**) method was the first to disregard such a view; in this method, the tower was represented by an inductance.

[2] The boldface numbers in parentheses refer to the references appended to this paper.

In 1950, a Sub-Committee of the AIEE presented a simple method (32) to the industry. In this method, lightning was considered as a current source, independent of the terminal impedance. Hence the surge-impedance concept of the stroke and the power-frequency voltage were neglected. The magnitudes of the currents in the stroke were expressed as probability curves, and the data obtained from 3214 magnetic link measurements were used. The Committee selected a 4 × 40 microsecond current wave and the tower was represented by a constant inductance of 20 microhenries. The number of strokes was considered as 100 per year per 100 miles at an isokeraunic level of 30. Otherwise the calculations were similar to that of the Harder and Clayton method. Several curves showed line outages as a function of tower-footing resistance and number of insulators and span lengths.

The AIEE method proved satisfactory, in a number of cases, in accurately predicting the line-outage rates. However, certain 345-kv lines in the United States (47), designed according to the AIEE method, have an outage rate several times greater than the predicted value. Essentially these lines are taller and have only one ground wire.

FACTORS NOT ADEQUATELY DEALT WITH IN THE AIEE METHOD

Bound Charges and Induced Voltages

The AIEE report neglected the induced voltage on the system due to bound charges that form during the advancement of the stroke towards the tower or midspan. Theoretical calculations (70) and experimental evidence (51) indicate that the induced charges increase rapidly as the stroke approaches the system. The prevailing opinion is that the voltages produced by the release of bound charge are very small compared to the flashover voltage of the insulator string (51). However, induced voltage cannot accurately be determined until the correct mechanism of the stroke is known.

Amplitude and Wave Shape of the Current

Strokes vary with respect to their duration, intensity, magnitudes, and current wave shapes they produce, as well as the frequency with which they occur. The variable nature of lightning makes it necessary to consider it as a probability phenomenon. A considerable amount of data has been collected on the current amplitude, by: Lewis and Foust (12), Foust in his Peruvian study (36), Hansson and Waldorf (23), Lewis and Foust (26), Grunewald (76), McCann (24), Bell (11), Gross and Lippert (19), Norinder (75), Hagenguth and Anderson (34) at the Empire State Building, and the recent investigations on the 345-kv lines of the Ohio Valley Electric Company (44). The data obtained may be classified broadly into three categories: (1) direct measurement of current on tower rods that are hit; (2) summation of ground-wire currents at both ends of a stricken span; and (3) measurement of currents in the tower legs, then multiplication of the single leg current by a suitable factor to obtain the total tower current, and then addition of the tower current and the earth wire currents to obtain the current in the stroke.

Currents in the first category are relatively free from errors. Measurements in the second category are also relatively error-free, provided the magnetic links on the ground wire are placed at such a distance from the tower top that the magnetic fields due to tower currents at the location of the magnetic link are negligible. Unfortunately such relatively error-free measurements are very few and the bulk of the data falls under the last category. In this method there are again several variations for obtaining the total current in a tower. Some investigators have multiplied the single tower-leg current by 4, and others have multiplied the sum of two tower-leg currents by 2, to obtain the total tower current. There are inherent errors and limitation of the magnetic links. The currents in the tower and in the ground wire may be out of phase (29) depending upon the span length and the grounding resistance. Therefore, when the out-of-phase tower current and ground current are added, the sum indicates a larger value than the actual stroke current. Recent transient analysis studies (63) have confirmed this view. The effect of the magnetic field of the current in the ground wire causes uneven current distribution in the tower legs and may even cause current reversal in one pair of legs. Subdivisions of currents in the various numbers of a lattice tower are not easily calculable. Attempts have been made (11,19,23) but the results are not in agreement. Unequal footing resistances are liable to change distribution of currents in the legs, and the measurements in one leg are not representative of current in the other leg.

The data obtained at the Empire State Building indicate low current amplitudes, contrary to data obtained on buildings of less elevation. A recent attempt (49) to explain this phenomenon by means of reflections of the current waves from several terminal points around Manhattan Island was inconclusive, although there was evidence that low current amplitude may be the result of the peculiar stroke mechanism characteristic of lightning strokes to this particular building.

In the AIEE Committee method the current probability curve was based on 3214 measurements. From the above it is obvious that an evaluation of the data of previous investigations is immediately needed for an accurate prediction of tower performance.

Wave Shape

The AIEE Committee agreed upon a time-to-crest of around 4 microseconds. Data concerning wave shape have been relatively few—the most recent being data obtained from actual oscillograms of current at the Empire State Building (37), data collected by McCann (24), and those obtained in Sweden (77). The data obtained at the Empire State Building are excellent since they are obtained from actual oscillograms, but the errors for measurements for fronts less than 1 microsecond seem to be very large. The other data may not directly give the time-to-crest. A study of the available data points out that higher currents are likely to be associated with higher times-to-crest. Attempts have been made to calculate the probable wave front (14) with a few assumptions, but these hypothesize the stroke mechanism itself and the theories of stroke mechanism are not at all conclusive at the present stage.

Nature of Wave Front

The time-to-crest of the current wave is not yet firmly established; therefore, it may be speculative to attempt to fix the type of wave front. At one time, the wave front was considered to increase exponentially up to the crest. Recently the theory of a concave front has been postulated (51). Laboratory tests on long sparks (35) confirm the general appearance of a concave wave front. Further, the concave wave front explains the beneficial purposes of counterpoises. However, there is no experimental evidence to confirm the concave nature of the wave front.

Frequency of Occurrence of Strokes to Transmission Lines

This is one of the most important factors in the prediction of outages of transmission lines. As a result of an 8-year investigation (23), it was postulated that the number of strokes per 100 miles per year at an isokeraunic level of 30 is 100. Laboratory studies (16) indicate that the number of strokes to the line is a function of tower height. It was assumed (25) that the number of strokes per square mile was equal to half the isokeraunic level; from this, the area of earth surface shielded from lightning by tower and ground wires is calculated. However, the validity of the assumption is not very convincing.

Ground Wire Under Surge Conditions

The AIEE method regards ground resistance as constant. However, there is considerable evidence that resistance under surge conditions decreases with current amplitude. The impulse resistance depends upon a number of factors such as soil resistivity, critical breakdown gradient of soil, and magnitude of surge current (15). From actual tests (17) it seems that the IR component of surge is low for clay while for gravel the resistance is not greatly reduced below a certain minimum value; it is only in these cases that counterpoises would be expected to be beneficial by reducing the initial level of ground-wire resistance to lower values for a-c. measurements. It is also known that a long counterpoise initially represents a surge impedance which is higher than the a-c. resistance and therefore its effectiveness seems to have been reduced, although field experience does not support this view. A possible explanation follows if a concave wave front is assumed; however, there is no experimental evidence for the concave wave front.

Insulator Flashover

The recent unpredicted flashovers on high voltage transmission lines have raised the question of the performance of suspension insulators, when subjected to voltages much higher than the normal critical impulse flashover values. Miller (**41**) contends that some of the flashovers might be due to steep wave-front surges, as evidenced by arc tracks that closely hug the contour of the flashed-over insulators, when the arcs are produced in the laboratory with steep-fronted surges. The experimental evidence available is not adequate to establish sound conclusions regarding the mechanism of flashover. The interesting point is that in the recent flashovers it was observed that the arc tracks closely hugged the contour of the flashed-over insulation. Experimental results (**52,53**) point out that such conditions can be obtained in the laboratory with voltages that are very large compared to the critical flashover voltage and the time-to-flashover is of the order 3 to 6 microseconds. The contour of the insulator, wave shape, polarity, and point of application of surge also affect the flashover voltage (**13,52,53**).

Representation of Tower as a Circuit Element

A tower is a very complex structure and so far, there is no accurate electromagnetic model of a tower. The analysis of fields surrounding a tower is a formidable task. Various authors preferred to represent it as an inductance or as a surge impedance from a circuit theory point of view.

The surge-impedance method used with the travelling wave theory has certain distinct features. If the time-to-crest of the current is less than the round-trip travel time of the tower, the voltage peak will occur at the instant when the current peak occurs. Thereafter it decreases along with the injected current. The main relief for the voltage comes from the reflected wave from the tower bottom. If the time-to-crest of the injected current wave is much greater than the round-trip travel time of the tower, the voltage initially increases until a time equal to the round-trip travel time of the tower. Thereafter it may more or less remain constant or decrease slowly or may slowly increase, depending upon the injected current wave and reflected wave. This will continue until the crest of the current wave is reached, after which the voltage wave begins to fall. After few reflections up and down the tower, the tower-top voltage is reduced to the tower-base voltage. If the current wave were to be a slow wave, the tower surge impedance would be wiped out by the time the current reaches peak value, and the tower voltage would be simply reduced to that of the base. In such a case the inductance representation yields a higher voltage. Thus this approach would be more useful if the current wave were to be a slow wave.

For linearly rising current wave, it is easy to show that the surge impedance gives a higher voltage than that given by the inductance method, whereas with the inductance approach the voltage becomes higher with an exponentially rising current wave and it has its crest at a very short time compared to the time-to-crest of the current wave. This time-to-crest of the resulting voltage waves becomes rather important while considering their relation to the voltage-time curve of the insulator string.

Validity of the Inductance and Surge Impedance Concepts

It is obvious that the currents in the ground wire and conductor produce a magnetic field that links with the tower and vice versa. So do the electric fields due to the charges. In the classical method, the mutual effects of the conductor and ground wire only are taken care of by coupling factors. The inductance and surge-impedance concept of tower do not take care of fields produced by charges and currents in conductor and ground wire. Similarly, the magnetic fields produced by the tower currents link with the loops formed by phase conductors and ground and induce a voltage of appreciable magnitude on the phase conductor. This aspect is not taken care of by the surge impedance nor by the inductance concepts.

In recent literature a good deal of effort is directed toward establishing whether the flashover of the insulator takes place in a fractional microsecond range or in a range greater than 2 microseconds. In the case of a tower of 150-ft. height, the electromagnetic wave travelling at the velocity of light takes 0.30 microsecond for round-trip travel. If one is concerned with what happens in the system during the travel of wave from tower top to tower bottom, representation of the tower by means of a circuit element is an extreme oversimplification, if not totally erroneous. The end effects also become important for a shorter time. Thus it is obvious that a solution based upon electromagnetic field equations gives the correct solution.

Analysis by Rigorous Methods

Analysis of the problem by means of field concepts is a recent one. Wagner (**18**), Szpar (**28**), Razevig and Rosenfield (**30**) calculated theoretically the induced voltages on lines and towers by the electric and magnetic fields around the stroke channel. Electrostatic measurements were made by Hagenguth (**51**), Akopian (**33**), Wagner (**40,70**), and Lundholm (**48**). Hagenguth derived an equation to estimate the voltage across the insulator string. In the above investigation, the same stroke mechanism (namely, a pilot streamer, the charge of which is neutralized by the upward moving charge from the tower top) is assumed. The induced voltages are due to (1) current fed into the tower top and ground-wire system, and (2) the current and charges travelling upward from the tower top, say for a stroke to tower. There are two distinct approaches—one is to neglect the effect of current and charges travelling upward from the tower top and consider only the effect of current fed into the system; the second one is to include both. The former derives its support from calculations (39,66) that indicate that for direct strokes on lines with ground wires the electric component for slow waves is small. Rusck (66) demonstrated that, for slow waves, the voltage is proportional to the time derivative of the induced field and height of the conductors. In other words, the inductance concept is proposed for slow waves. The second approach is advocated by Dr. Wagner who demonstrated that the effect of charges above the tower is the dominating factor, especially for fast waves. However, it is gratifying to see that there is good agreement among the results obtained by the two different approaches, insofar as the effects of the current fed into the system are concerned.

EXPERIMENTAL WORK

Attempts have been made (68) to obtain the instantaneous transfer function between the voltage across the insulators and the current in the stroke with a step-function current, and the results obtained agree reasonably well with those from the theoretical calculations (70). With regard to a test with slow waves, simulation of the electric component of the stroke seems to be difficult. But the calculations (70) indicate that the effects of charges and current in the stroke are all the more important with fast waves. If the electric component is neglected, the transfer impedance behaves like that of an inductance, which is time-varying. This is amply demonstrated by theory as well (68,70,66). Full scale model tests (67) have been carried out to obtain the instantaneous transfer function; however, it seems that electric components have not been exactly duplicated in the simulation of the stroke.

RECENT EXCESSIVE FLASHOVERS AND SUGGESTED REMEDIAL MEASURES

Of the total 110 flashovers reported on 345-kv lines (47), 11 are believed to be probable shielding failures. Of the remaining, 75 flashovers occurred only on the top-phase insulators and 17 flashovers only on the middle-phase insulators. Both the top-phase insulators were flashed over in two cases and both the middle-phase insulators in three cases. There were also two multiphase flashovers. If the voltage generating mechanism is considered by the surge impedance concept of a tower and if travelling wave theory is used, these flashovers seem to be due to marginal voltages. In accordance with travelling wave theory, the voltage at the top cross arm continues to increase until it is alleviated by the reflection from tower base. The voltage at the middle cross arm is lower than that at the top cross arm. But the coupling factor is lower for the middle-phase conductor. Therefore the voltage across the middle-phase insulator string is likely to be more than that across the top-phase insulator string, depending on relative heights of these conductors, and the former is alleviated earlier than the latter. At this stage the power frequency voltage would be the determining factor for the flashover of the top- or the middle-phase insulator string, depending on the instant of flashover. Thus these may be termed as marginal flashovers and the above evidence supports them. The theory was originally put forward by Miller (**41**,**60**) and they were termed anomalous flashovers.

From the above analysis, the voltages across the insulator strings are functions of the geometry of the line and tower configuration for given conditions of footing resistance, ground wire, corona radius, and stroke current time function. Rigorous studies based upon electromagnetic field equations have indicated the profound influence of tower geometry on the insulator strings. This is also confirmed by the fact that the 345-kv lines and 138-kv lines, which experienced greater flashover rates, are essentially taller and have one ground wire.

Suggested Remedial Measures

The reduction of tower height and of ground wire surge impedance and the increase of coupling by the use of two ground wires appear to be helpful. In the case of extra high voltage lines, delta configuration of conductors may be used to meet the required clearances. Use of two ground wires has proved to be beneficial and can be relied upon. If the degree of coupling needed is much more than what is obtained from two ground wires, a third ground wire may be employed. It was shown that (**22**) by means of a third ground wire, located underneath the conductors, an increase of 25 to 45 per cent in coupling factor is possible. A 69-kv line (**57b**) designed with one ground wire on the top and the other vertically below the top ground wire and in between the conductors has a satisfactory record.

CONCLUSIONS

There is an immediate need to re-evaluate the magnetic link data and the consequent current amplitudes and to develop accurate reliable instrumentation to measure currents and their wave shape.

Currently available evidence indicates that the effect of bound charges is negligible in inducing a voltage across the insulators.

There is a good amount of evidence that the lightning current waves are slow waves, but the exact nature of the wave shape (concave, exponential or linearly rising) can only be verified by experimentation. If the theory of the slow wave is accepted, the induced voltage will turn out to be proportional to the rate of change of current. This inductive nature of the transfer function is also evidenced from experimental measurements. With the inductance approach, the wave shape of the voltage and its time-to-crest vary differently with an exponential, linearly rising, or concave front. These become very significant when considered in conjunction with the insulator voltage time curves.

The theory of slow waves is an accepted concept. It is only recently that a few engineers have proposed the hypothesis of steep-fronted surges, but there is not enough experimental evidence to support this view. The surge impedance concept of a tower is useful for steep-fronted current waves and the inductance concept of the tower is useful for slow waves. However, these cannot represent the mutual effects of tower, conductor, and ground wire. The amount of error obtained by the methods using these concepts seems to be relatively low but an accurate assessment should await further analysis by means of rigorous methods.

The behavior of ground resistance should also be considered.

There is good evidence that tower geometry influences the voltage across the insulators. In the absence of any reliable methods to estimate the voltage, a comparison method may be developed to predict the outages of a new line, making use of the available performance record of a carefully chosen reference line. However, based upon experience, the use of two ground wires, or three, if necessary and economical, and the use of delta towers to reduce the height, should prove useful.

Experimental verifications of theoretical calculations have been very few in this field. They prove extremely useful and can either bolster or reject the various theories that are being advanced.

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REFERENCES

(1) C. L. FORESCUE AND R. N. CONWELL, "Lightning Discharges and Line Protective Measures," *AIEE Trans.*, Vol. 50, pp. 1090–1100 (1931).

(1a) W. W. LEWIS AND C. M. FOUST, "Direct Strokes to Transmission Lines," *G. E. Rev.*, Vol. 34, p. 452 (1931).

(2) EDGAR BELL AND A. L. PRICE, "Lightning Investigation on the 220 KV System of Pennsylvania Power and Light Company," *AIEE Trans.*, Vol. 50, pp. 1101–1110 (1931).

(3) C. A. JORDAN, "Lightning Computation for Transmission Lines with Overhead Ground Wires," *G. E. Rev.*, Vol. 37, pp. 130–137, 180–185, 243–50 (1934).

(4) W. W. LEWIS AND C. M. FOUST, "Lightning Investigation on Transmission Lines," *Elec. Eng.*, Vol. 53, pp. 1180–1186 (1934).
(5) A. C. MONTEITH, "Transmission Line Design Estimates," *Electrical J.*, East Pittsburg, pp. 72–75 (1934).
(6) L. V. BEWLEY, "Protection of Transmission Lines Against Lightning," *G. E. Rev.*, Vol. 40, pp. 180–188 (1937).
(7) D. J. MALAN AND H. COLLENS, "Progressive Lightning III—The Fine Structure of the Returning Lightning Stroke," *Proc. Roy. Soc. London*, Vol. 162, pp. 145–203 (1937).
(8) P. J. RYLE, "Direct Lightning Stroke to Towers and Effects of Wave Fronts, Footing Resistance and Tower Height," *CIGRE*, Paris, 1937.
(9) C. L. FORTESCUE, "Direct Strokes and Not Induced Surges—Chief Cause of High Voltage Line Flashovers," *AIEE Trans.*, Vol. 56, pp. 546–549 (1937).
(10) L. V. BEWLEY, "Protecting Transmission lines at Tall Tower River Crossings," *Elec. World*, New York, March, 1938.
(11) EDGAR BELL, "Lightning Investigations on 220 KV systems—III," *AIEE Trans.*, Vol. 59, pp. 822–887 (1940).
(12) W. W. LEWIS AND C. M. FOUST, "Lightning Investigations on Transmission Lines—VII," *AIEE Trans.*, Vol. 59, pp. 227–234 (1940).
(13) J. H. HAGENGUTH, "Volt Time Areas of Impulse Sparkover," *AIEE Trans.*, Vol. 60, pp. 803–810 (1941).
(14) C. E. R. BRUCE AND R. H. GOLDE, "The Lightning Discharge," *Jour. IEE*, Vol. 88, pp. 487–505 (1941).
(15) Discussion by H. M. TOUNE, *AIEE Trans.*, Vol. 60, p. 718 (1941).
(16) C. F. WAGNER, G. D. MCCANN AND G. L. MACLANE, Jr., "Shielding of Transmission Lines," *AIEE Trans.*, Vol. 60, pp. 313–328 (1941).
(17) P. L. BALLASCHI, R. E. ARMINGTON AND A. E. SNOWDEN, "Impulse and Sixty-cycle Characteristics of Driver Grounds—II," *AIEE Trans.*, Vol. 61, pp. 349–362 (1941).
(18) C. F. WAGNER AND G. D. MCCANN, "Induced Voltages on Transmission Lines," *AIEE Trans.*, Vol. 61, p. 916 (1942).
(19) I. W. GROSS AND G. D. LIPPERT, "Lightning Investigation on 132 KV Transmission System of the American Gas and Electric Company," *AIEE Trans.*, Vol. 61, pp. 178–185 (1942).
(20) I. G. HEMSTRUT, W. W. LEWIS AND C. M. FOUST, "Study of Driven Rods and Counterpoises in High Resistance Soil on Consumers Power Company 140 KV Systems," *AIEE Trans.*, Vol. 61, pp. 628–633 (1942).
(21) Discussion by J. H. HAGENGUTH, *AIEE Trans.*, Vol. 61, pp. 1001–1002 (1942).
(22) G. D. MCCANN, "The Effect of Corona on Coupling Factors Between Ground Wires and Phase Conductors," *AIEE Trans.*, Vol. 62, pp. 818–826 (1943).
(23) E. HANSSON AND S. K. WALDORF, "An Eight Year Investigation of Lightning Currents and Preventive Lightning Protection on Transmission System," *AIEE Trans.*, Vol. 63, pp. 251–258 (1944).
(24) G. D. MCCANN, "Measurements of Lightning Currents in Direct Strokes," *AIEE Trans.*, Vol. 63, pp. 1157–1164 (1944).
(25) R. H. GOLDE, "The Frequency of Occurrence and Distribution of Lightning Flashes to Transmission Lines," *AIEE Trans.*, Vol. 64, pp. 902–910 (1945).
(26) W. W. LEWIS AND C. M. FOUST, "Lightning Investigations on Transmission Lines—VIII," *AIEE Trans.*, Vol. 64, pp. 107–115 (1945).
(27) AIEE Lightning and Insulator Working Group, "Lightning Performance of 220 KV Transmission Lines—II," *Elec. Eng.*, Vol. 65, pp. 70–76 (1946).
(28) S. SZPOR, "A New Theory of Induced Over-Voltages," *CIGRE*, Paper no. 308, 1948.
(29) R. H. GOLDE, "Lightning Currents in Transmission Lines," *CIGRE*, Paper no. 311, 1948.
(30) D. V. RAZEVIG AND A. S. ROZENFIELD, "Calculation of Electrostatic Component of the Induced Over Voltages," *Electrochestvo*, Vol. 10, pp. 31–36 (1949).

(31) E. L. HARDER AND J. M. CLAYTON, "Transmission Line Design and Performance Based on DIRECT Lightning Stroke," *AIEE Trans.*, Vol. 68, pt. 1, pp. 439–446 (1949).

(32) AIEE Committee Report, "A Method of Estimating Lightning Performance of Transmission Lines," *AIEE Trans.*, Vol. 69, pt. II, pp. 1187–1196 (1950).

(33) A. A. AKOPIAN, "Experimental Investigation of Voltages Induced in a Line Model," *Electrochestvo*, Vol. 11, pp. 22–28 (1950).

(33a) Discussion by J. H. HAGENGUTH, *AIEE Trans.*, Vol. 69, pt. II, p. 1549 (1950).

(34) J. H. HAGENGUTH AND J. G. ANDERSON, "Lightning to the Empire State Building—III," *AIEE Trans.*, Vol. 71, pt. III, pp. 641–648 (1952).

(35) A. F. ROHLFS AND W. J. DAGNAN, "Sixty-cycle and Impulse Sparkover of Large Gap Spacings," *AIEE Trans.*, Vol. 71, pt. III, pp. 455–460 (1952).

(36) C. M. FOUST, B. C. MAINE AND C. LEE, "Lightning Stroke Protection at High Altitudes in Peru," *AIEE Trans.*, Vol. 72, pt. III, pp. 383–392 (1952).

(37) J. H. HAGENGUTH AND I. G. ANDERSON, "Lightning to Empire State Building—Part IV," *AIEE Trans.*, Vol. 72, pt. III, pp. 645–649 (1953).

(38) S. SZPOR, "Supplement to the Theory of Induced Voltages for Lines with Earth Conductors," *Archiwum Electrotechnik*, Tom III, pp. 187–188 (1953).

(39) R. H. GOLDE, "Lightning Surges on Overhead Distribution Lines Caused by Direct and Indirect Lightning Stroke," *AIEE Trans.*, Vol. 73, pt. III, p. 445 (1954).

(40) C. F. WAGNER, "A New Approach to the Calculation of Lightning Performance of Transmission Lines," *AIEE Trans.*, Vol. 75, pt. III, pp. 1233–1256 (1956).

(41) C. J. MILLER, "Anomalous Flashovers on Transmission Lines," *AIEE Trans.*, Vol. 75, pt. III, pp. 897–907 (1956).

(42) E. F. KONCEL, "Potential of Transmission Line Tower Top when Struck by Lightning," *AIEE Trans.*, Vol. 75, pt. III, pp. 457–462 (1956).

(43) W. S. PRICE, S. C. BARTLETT AND E. S. ZOBEL, "Lightning and Corona Performance of 330 KV Lines on the American Gas and Electric Company and Ohio Valley Electric Corporation," *AIEE Trans.*, Vol. 75, pt. III, pp. 583–592 (1956).

(44) R. H. SCHLOMANN, W. S. PRICE, I. H. JOHNSON AND J. G. ANDERSON, "1956 Lightning Field Investigation on OVEC 345 KV System," *AIEE Trans.*, Vol. 76, pt. III, pp. 1447–1456 (1957).

(45) R. W. CASWELL, E. F. KONCEL, N. R. SCHULTZ AND I. B. JOHNSON, "Lightning Performance of 138 KV Twin Circuit Transmission Lines of Commonwealth Edison Company," *AIEE Trans.*, Vol. 76, pt. III, p. 1480 (1957).

(46) A. J. SCHULTZ, G. D. BREUER, W. S. PRICE AND R. H. SCHLOMANN, "Field Studies of the Surge Response of a 345 KV Transmission Tower and Ground Wire," *AIEE Trans.*, Vol. 76, pt. III, p. 1392 (1957).

(47) H. L. RONDEN, E. S. ZOBEL AND G. D. LIPPERT, "Two Year Lightning Experience on 345 KV Lines," *AIEE Trans.*, Vol. 76, pt. III, pp. 954–960 (1957).

(48) R. LUNDHOLM, R. B. FINN AND W. S. PRICE, "Calculation of Transmission Line Voltages by Field Concepts," *AIEE Trans.*, Vol. 76, pt. III, pp. 1271–1283 (1957).

(49) I. B. JOHNSON AND A. J. SCHULTZ, "A Hypothesis Concerning Lightning Phenomena and Transmission Line Flashover," *AIEE Trans.*, Vol. 76, pt. III, pp. 1470–1471 (1957).

(50) C. M. FOUST AND B. V. BHIMANI, "A New Voltage Time Recorder for Transient Measurements," *AIEE Trans.*, Vol. 76, pt. 1, pp. 253–262 (1957).

(51) J. H. HAGENGUTH AND J. G. ANDERSON, "Factors Affecting the Lightning Performance of Transmission Lines," *AIEE Trans.*, Vol. 76, pt. III, pp. 1379–1393 (1957).

(52) A. F. ROHLFS AND H. F. FIEGAL, "Impulse Flashover Characteristics of Long Suspension Insulators," *AIEE Trans.*, Vol. 76, pt. III, pp. 1321–1329 (1957).

(53) B. E. KINGSBURY, "Suspension Insulator Flashover Under High Impulse Voltages," *AIEE Trans.*, Vol. 76, pt. III, pp. 1429–1433 (1957).

(54) L. O. BARTHOLD, "An Approximate Transient Solution of Tapered Transmission Lines," *AIEE Trans.*, Vol. 76, pt. III, pp. 1556–1561 (1957).

(55) E. S. ZOBEL, "A. G. & E. Field Tests on New Tower and Twin Bundled Conductors at 345 KV," *Electrical World*, Dec. 9, 1957.

(56) I. B. JOHNSON AND A. J. SCHULTZ, "Analytical Studies on Lightning Phenomena Involving Towers, Insulator Strings, and Transmission Lines," *AIEE Trans.*, Vol. 76, pt. III, pp. 1310–1316 (1957).
(57a) R. W. CASWELL, E. F. KONCEL AND ERIC T. B. GROSS, "Analytical Studies of Lightning Performance of One and Two Ground Wire 138 KV Double Circuit Lines of the Commonwealth Edison Company," *AIEE Trans.*, Paper 58–144, 1958.
(57b) Discussion by E. R. WHITEHEAD, *AIEE Trans.*, Paper 58–166,1958.
(58) C. F. WAGNER AND A. R. HILEMAN, "Lightning Stroke," *AIEE Trans.*, Vol. 77, pt. III, pp. 229–242 (1958).
(59) C. F. WAGNER, C. M. LANE AND C. M. LEAR, "Arc Drop During Transition from Spark Discharge to Arc," *AIEE Trans.* Paper 58–176, 1958.
(60) C. J. MILLER, "Anomalous Flashovers on Transmission Lines—II," AIEE Conference Paper 58–189, 1958.
(61) J. G. ANDERSON AND J. H. HAGENGUTH, "Magnetic Fields Around a Transmission Line Tower," *AIEE Trans.*, Vol. 77, pt. III, pp. 1644–1650 (1958).
(62) Discussion by C. F. WAGNER, *AIEE Trans.*, Vol. 77, pt. III, pp. 1650 (1958).
(63) A. J. SCHULTZ, I. B. JOHNSON AND W. S. PRICE, "Lightning Currents in Towers and Ground Wires," *AIEE Trans.* Paper 58–403, 1958.
(64) S. B. GRISCOM, "Prestrike Theory and Other Effects in Lightning Stroke," *AIEE Trans.*, Vol. 77, pt. III, pp. 919–983 (1958).
(65) S. B. GRISCOM, J. W. SKOOGLUND, A. R. HILEMAN, "Influence of Prestrike," *AIEE Trans.*, Vol. 77, pt. III, pp. 933–941 (1958).
(66) S. RUSCK, "Induced Lightning Overvoltages on Power Transmission Lines with Special References to the Overvoltage Protection of Low Voltage Networks," *Trans. Roy. Inst. Tech.*, Stockholm, Sweden, No. 120, 1958.
(67) H. R. ARMSTRONG, L. O. BARTHOLD AND A. R. SHULTZ, "Response of a 345 KV Transmission Tower to a Simulated Lightning Stroke," A.I.E.E. Conference Paper 59–275, 1959.
(68) J. H. HAGENGUTH, J. G. ANDERSON AND F. A. FISCHER, "Determination of Lightning Response of Transmission Lines by Means of Geometric Models," *AIEE Trans.*, Vol. 78, pt. III, pp. 1725–1736 (1960).
(69) J. G. ANDERSON AND R. V. GIACOMONI, "The Teinograph—A New High Voltage Surge Recorder," paper presented at the AIEE Middle Eastern District Meeting, Baltimore, Md., 1959.
(70) C. F. WAGNER AND A. R. HILEMAN, "A New Approach to the Calculation of Lightning Performance of Transmission Lines—II," *AIEE Trans.*, Vol. 78, pt. III, pp. 996–1021 (1959).
(71) Central Station Engineers, "Electrical Transmission and Distribution Reference Book," Pittsburgh. Westinghouse Electric Corporation, 1950.
(72) L. V. BEWLEY, "Travelling Waves on Transmission Systems," New York, John Wiley & Sons, Inc., 1951.
(73) W. W. LEWIS, "Protection of Transmission Systems Against Lightning," New York, John Wiley & Sons, Inc., 1950.
(74) EDWARD BECK, "Lightning Protection of Electrical Systems," New York, McGraw-Hill Book Co., Inc., 1954.
(75) H. NORINDER, "Some Recent Measurements of Induced Surges," CIGRE, Report No. 303 (1939).
(76) H. GRUNEWALD, "Results of a 4-Year Study of the Location and Intensity of Lightning on Aerial Lines," CIGRE, Report No. 316 (1937).
(77) N. HYLTEN-CAVALLIUS AND A. STRÖMBERG, "The Amplitude, Time to Half Value and Steepness of Lightning Currents," *ASEA Jour.*, Vol. 29, pp. 129–134 (1956).
(78) N. RAMA RAO, "Lightning Performance of Transmission Lines—Analysis and Evaluation," M. S. thesis, University of Wisconsin, 1959.